PETROLOGICAL STUDIES IN THE ORDOVICIAN OF NEW SOUTH WALES. II.

THE NORTHERN EXTENSION OF THE COOMA COMPLEX.

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(Plate v; five Text-figures.)

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Contents.

I. *Introduction.*

The area under consideration lies within the Parishes of Murrumbucka, York, Cosgrove, Callaghan, Woolumla and Bunyan, immediately north of the region described and designated as the Cooma Complex in the first paper of this series (Joplin, 1942).

In attempting to unravel the metamorphic and tectonic history of the Cooma Complex, attention was paid only to that area of Ordovician rocks unaffected by either the Silurian intrusives or Silurian earth movements. It is shown below that there is an extension of the Cooma Complex into this northern area and that it has been invaded by, and often locally altered by, the Silurian intrusives. Moreover, the lower grade Ordovician rocks bear an imprint of the Silurian diastrophism. Thus the whole Cooma Region, which includes both southern and northern areas, must be studied before an attempt is made to interpret the tectonic history.

II. CORRELATION WITH THE COOMA COMPLEX.

In the earlier paper (Joplin, 1942) the Ordovician intrusives and progressive metamorphism and granitization of the Ordovician strata were described in a region extending about 8 miles north, 18 miles south and 10 miles west of the town of Cooma. Owing to the occurrence of extensive sheets of basalt on the east, attention was paid mainly to the western area where six metamorphic zones were traced. Reference to Plate v and to Fig. 4 in the present paper will show that these western zones have a northerly extension. In 1942, several zones were roughly mapped near the railway loop just north-east of Cooma Railway Station but they were not described in the text of the first paper as it was recognized that a tongue of Silurian gneiss, invading these, might be in part responsible for their metamorphism, and as this small area was the only one in which the eastern zones could be studied in the southern area.

From a study of the northern area, however, it is obvious that the eastern zones are much narrower than those on the west and that, like the western zones, they may be traced further north. The difficulties attending the mapping of these zones are discussed below.

Owing to distinct lithological differences the Ordovician rocks exposed near Cooma were divided into the Coolringdon and Binjura Beds. It was suggested that the structure was that of an overturned asymmetrical anticline dipping to the east with the Coolringdon Beds overlying the Binjura Beds. Within the northern area both Binjura and Coolringdon Beds occur as well as higher units of the Ordovician, immediately beneath the Silurian. These appear to be developed only on the east, and just south of Bunyan they overlie the Coolringdon black slates. Owing to their great development in the Parish of Bransby, about 16 miles further north, it is proposed to call them the Bransby Beds. The lithology of these beds differs from that of both the underlying Coolringdon and Binjura Beds.

III. Ordovician Rocks.

1. BRANSBY BEDS.

These beds consist largely of volcanic and pyroclastic material, although pelites occasionally occur, thinly bedded limestones alternate with tuffs near the base and lenses of limestone occur near the top (Fig. 1). Quartz-felspar-porphyries invade the rhyolites and tuffs and are probably co-magmatic with them.

South of Bunyan these rocks overlie the typical black slates of Coolringdon-type and if the main structure is an anticline (see Fig. 5) then the Bransby Beds appear to be the highest units of the Ordovician as developed at Cooma. Browne (1943) considers that the structure is a syncline and in this case the Bransby Beds would be at the base of the Ordovician succession.

With the exception of a felsite sill intrusive into the Coolringdon Beds, no trace of the Bransby Beds has been recorded from the western limb of the anticline. This may be due to one of three causes. Firstly, granites invade and basalt overlies much of the western area where these beds would be expected to occur; secondly, they may have thinned out and never have been developed on the western limb (Fig. 5); and thirdly, they may, especially as they consist of volcanic and littoral deposits, represent a different facies on the same stratigraphical horizon as the deeper-water Coolringdon Beds. For the purpose of the present paper they will be considered as a separate unit overlying the Coolringdon Beds and immediately underlying the Upper Silurian.

(i). *Limestones.*

Near the base of the Bransby Beds narrow seams of limestone only a few inches in width are interbedded with tuffs, but occasionally larger lenticular masses occur and two of these are to be found south of Bunyan and east of the main road.

The most southerly occurs in the railway cutting in Pors. 192/181, Parish of Bunyan, where it is associated with pelites and porphyry. It is a banded rock consisting of an uneven mosaic (0·5 mm.–0·01 mm.) of calcite with very narrow collinear masses of carbonaceous material.

A larger lenticular mass of limestone occurs about 3½ miles north of Cooma and just east of the main road in Por. 152, Parish of Bunyan. This is a white, flinty rock that has been silicified and contains rare calcite grains in a mosaic of quartz with fairly abundant tremolite, diopside and sphene. The narrow bands of limestone associated with tuff have also suffered silicification and consist almost exclusively of quartz and epidote.

With the exception of a limestone cropping out on the main road near Pearman's Hill, the lenses shown at the top of the Bransby Beds in Fig. 1 do not occur within the area at present under discussion, but mention is made of them here as I have examined and collected them during a geological excursion with Dr. W. R. Browne, who has mapped this area as well as much of the country to the north. Furthermore, some of these marbles exhibit evidence of having suffered both dynamic and contact-metamorphism, and as this evidence is used in developing arguments regarding the metamorphic and tectonic histories of the area, it seems wise to briefly describe these rocks.

The least altered type comes from Cotter's Crossing on the Murrumbidgee River, about 4 miles south-west of Michelago in Por. 17, Parish of Yarara. This is an even-grained marble (about 0·1 mm.) and the twin lamellae of the calcite are somewhat strained.

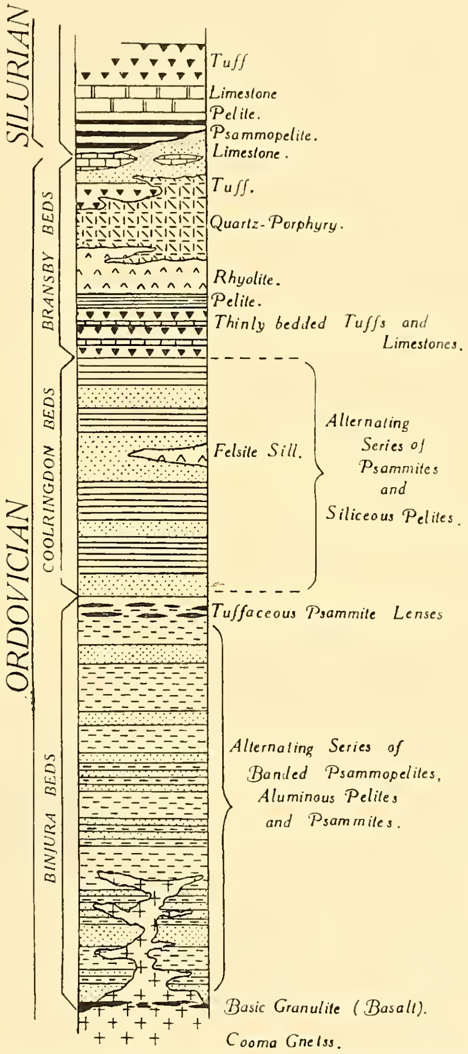

Fig. 1.—Columnar section showing approximate sequence of the Ordovician as exposed in the Cooma Region. The thickness of beds has not been measured and the section is therefore not drawn to scale.

Further south in Pors. 4, 8, 9, 10 and 78, Parish of Bumbalong, contact phenomena are well pronounced and aggregates of tremolite, diopside, sphene, plagioclase and occasionally a little biotite occur in nodules in a mosaic of calcite and dolomite. The silicate minerals tend to give the rock an augen-structure. The hard silicates have resisted crushing and according to Harker (1932, p. 170) the coarser patches of carbonate in the corners of the 'eyes' are patches of the original limestone that have been protected. The carbonates between the 'eyes' show a slight schistosity, and secondary twin lamellae are curved and contorted. Needles of amphibole, parallel to the direction of schistosity, are not uncommonly associated with the carbonates. The calcite grains are slightly elongated with sutured boundaries and the grains of dolomite are more equidimensional and sub-idioblastic. These rocks were originally dolomitic limestones with argillaceous impurities.

A little further south in Pors. 107 and 108, Parish of Bransby, two lenses of marble occur just above the rhyolites and immediately beneath the Upper Silurian. These were originally very pure limestones and have recrystallized into marbles showing little evidence of contact-metamorphism. Dynamic metamorphism is evidenced by elongated porphyroblasts of calcite up to 2·5 mm. and by lenticular aggregates of smaller calcite grains which are surrounded by somewhat elongated grains exhibiting secondary twinning with curved lamellae.

A limestone from the main road near Pearman's Hill in the north-easterly part of the present map (Plate v) contains pelitic bands that have recrystallized as quartz-sericite-schists with parallel bands of carbonaceous material and a slight augen-structure. Elongated lenses of calcite occur within the pelitic seams, and though a few coarser grains of diopside have sometimes developed in the immediate vicinity of these lenses, there is no sign of reaction between calcite and quartz or between calcite and sericite. The limestone seams of this rock consist of elongated grains of quartz, numerous small granules of diopside, a little iron ore and small greyish patches of carbonaceous material.

These metamorphosed limestones will be referred to again (p. 175) in dealing with the contact-aureole of the Silurian gneisses. It is evident that contact-metamorphism ante-dated shearing, but so far as the limestones are concerned it is not possible to tell whether this was preceded by a still earlier dynamic metamorphism.

(ii). *Pelites, Psammites and Tuffs.*

Pelites occur on a fairly restricted horizon just above, and sometimes interbedded with, limestones and tuffs near the base of the Bransby Beds. The pelites are mainly buff-coloured rocks with a slight sheen and in the field appear to be in a fairly low grade of metamorphism.

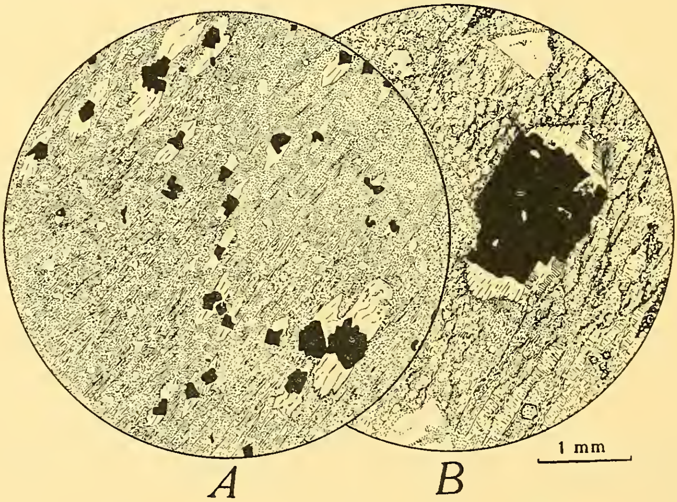

Fig. 2 (× 12).

A. Pelite, Por. 69/87, Parish of Callaghan, consisting chiefly of chlorite, sericite and chalcedony and showing "eye" structure. The centre of the "eye" consists of limonitized pyrites and the corners of fibrous chalcedony.

B. Banded pelite and tuffaceous psammite, Por. 69, Parish of Callaghan. The pelitic band (right) consists of chlorite with some elongated lenses showing a transverse arrangement of the fibres. Small crystals of apatite and granular magnetite are also present. The band of tuffaceous psammite contains corroded crystals of quartz and felspar in a fine mass consisting of quartz, sericite and chlorite. A large crystal of limonitized pyrites is fringed with chalcedony and chlorite.

Under the microscope they are seen to consist of a scaly aggregate of which the only recognizable constituents are chlorite, sericite and quartz together with a little carbonaceous and chalcedonic material. "Eye" structure is fairly common (Figs. 2A, 2B). The centre of the "eye" consists of limonitized pyrites and the corners of fibrous chalcedony. Harker (1889, 1932) believes this structure to be indicative of dynamic metamorphism, the hard pyrites crystals, having resisted crushing, have caused the development of lenticular spaces in the zone of least pressure. In discussing the origin of "pressure-shadows" of feathery quartz about pyrites crystals, Pabst (1931) refers to the work of Mügge (1928), who considers that the growth of the quartz crystals is contemporaneous with the opening of the lenticular cavity and that the cavity is completely filled with feather quartz only when the rate of opening synchronizes with the rate of growth. Harker (1889), on the other hand, considers that these openings, due to "lateral thrust . . . were filled at a later date by crystalline quartz". The idiomorphic pyrites crystals transgress the cleavage of the slate and, as pointed out by Knopf (1929), this indicates that the pyrites was introduced after the rock had suffered dynamic metamorphism and received a cleavage. These rocks therefore exhibit three impresses of metamorphism: first, low-grade dynamic that produced a cleavage and possibly elevated the rocks to the chlorite-zone, then a low-grade contact alteration or metasomatism responsible for the introduction of pyrites, and finally a dynamic metamorphism that produced the "eye" structure. It will be noted that the last two types of metamorphism were recognized in the limestones.

The following partial analysis (I) indicates that the pelites are siliceous, but not so markedly siliceous as the average of three typical pelites (II) from the Coolringdon Beds (Joplin, 1942, p. 161). Their mineralogy testifies to this.

	I.	II.
SiO_2	75·63	81·59
Al_2O_3	12·92	10·48
Fe_2O_3	4·23	1·56
MgO	1·79	0·53
CaO	0·21	0·22
H_2O	2·36	2·21

A banded pelite with coarse tuffaceous seams gives evidence of the same three stages of low-grade metamorphism. In the pelitic part of this rock, chlorite forms very elongated lenses with a transverse arrangement of the flakes; this, Harker (1932, p. 211) considers indicative of an early stage of dynamic metamorphism.

Small idiomorphic crystals of apatite are abundant in this rock and may have recrystallized from the original tuffaceous material or may have been introduced with pyrites at a later stage. Fig. 2B shows a large pyrites crystal with chlorite as well as chalcedony filling the cavity produced in the region of least pressure. The chlorite has grown inwards from the wall of the cavity and outwards from the surface of the pyrites, but does not completely fringe either surface, and seems to be sporadic in its growth. Furthermore, it fills small spaces between the chalcedony crystals.

The tuffaceous seams of this rock show some admixture with psammitic material and consist of rounded grains of quartz in an aggregate of sericite and elongated wisps of chlorite that are arranged to produce a somewhat lenticular pattern and a slight schistosity. Corroded and fractured quartz crystals and subidiomorphic crystals of felspar up to 3 mm. are set in this base.

A fine cherty rock from the western side of the river in Por. 40, Parish of York, consists mainly of tuffaceous material. This contains small sericitized felspar crystals in a fine base of chlorite and minute grains of clinozoisite and iron ore. A very similar type of sheared tuff or porphyry occurs in narrow bands interbedded with epidotized limestones east of the main road in Por. 49, Parish of Bunyan. In these rocks, however, the grainsize is a little coarser, corroded and fractured crystals of quartz are numerous and a little biotite has developed in the recrystallized chloritic base. The presence of the biotite seems to suggest slight contact-metamorphism.

There are all possible admixtures of tuff, pelite and psammite among the rocks on this horizon. Those occurring on the eastern side of the main road in the Parish of Callaghan are of low grade—certainly not higher than chlorite-zone, but a rock cropping out a short distance west of the road near Pearman's Hill exhibits evidence of greater stress. It is a psammopelite and contains recrystallized lenticular aggregates of quartz surrounded by flakes of green mica. The more micaceous patches show a false-cleavage and tiny transverse quartz veins indicate a small-scale folding. This rock, like the tuff from Por. 40, Parish of York, is higher in the Bransby Beds and rare pelitic seams occur associated with the limestones near the top of these beds. One of these has been described as occurring in seams in the limestone near Pearman's Hill and seems to be more siliceous and more carbonaceous than those of a lower horizon.

(iii). *Rhyolites and Rhyolitic Tuffs.*

Rhyolites and rhyolitic tuffs occur in the Bransby Beds (Fig. 1) and are exposed in an elongated strip extending for about 17 miles from just south of Colinton Gorge, in the Parish of Bransby, to a little east of Bunyan. They exhibit varying degrees of shearing and all appear to have suffered metamorphism of a purely dynamic character.

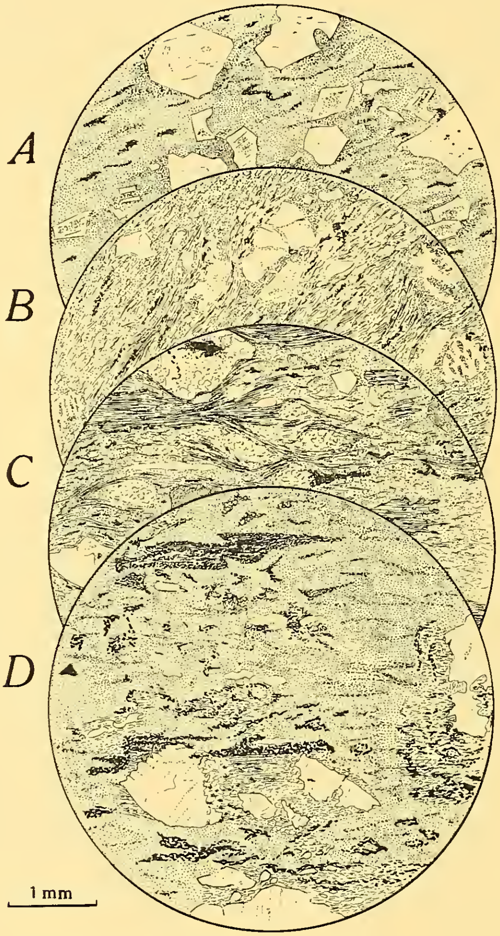

Fig. 3.

Dynamic Metamorphism of Rhyolites (× 12).

A. Rhyolite showing idiomorphic phenocrysts of quartz partly corroded and smaller somewhat altered phenocrysts of felspar in a cryptocrystalline groundmass with fluidal fabric.

B. Sheared rhyolite showing fractured quartz phenocrysts and the development of much sericite in a lepidoblastic base.

C. Sheared rhyolite (originally a biotite-bearing type) showing augen-structure with crushed, stretched and granulated quartz phenocrysts wrapped round by flakes of biotite and sericite. Smaller quartz phenocrysts have resisted crushing.

D. Crushed rhyolite (almost a mylonite) showing stretched and granulated phenocrysts of quartz and stretched and contorted flakes of biotite completely pseudomorphed by granular magnetite in a finely crushed base.

The least altered type, occurring in the core of a lenticular mass of sheared rhyolite in Por. 200, Parish of Bransby, contains phenocrysts of quartz and orthoclase and occasional crystals of plagioclase in a felsitic groundmass. Under the microscope the phenocrysts are seen to vary from about 2 mm. to 0·3 mm. in size. The quartz crystals are idiomorphic and somewhat corroded and show undulose extinction, and the orthoclase often has an altered central core of sericite (Fig. 3A) and may exhibit a fine polysynthetic twinning due to strain. A fine dust of iron ore is arranged along lines of flow in a cryptocrystalline groundmass which may represent devitrified glass. That this fine groundmass probably consists of an aggregate of quartz and felspar is suggested by the recrystallized base and by the chemical composition of a slightly more sheared type (Fig. 3B and Anal. I below). In this more altered rock, quartz phenocrysts are cracked and recemented by minute grains of granular quartz, and orthoclase shows alteration into sericite. The groundmass consists mainly of a fine recrystallized aggregate of quartz and orientated flakes of white mica. In handspecimen this rock shows a slight schistosity. Other rhyolites of this grade of metamorphism contain flakes of bleached or chloritized biotite that have discharged magnetite dust. These rocks apparently represent a type which originally contained phenocrysts of biotite.

In a higher grade of metamorphism both rock-types show a slight augen-structure, the 'eyes' consisting of elliptical masses of granular quartz (Fig. 3C). Some of the smaller quartz phenocrysts appear, however, to have resisted crushing. Orthoclase phenocrysts, though completely kaolinized, still retain their outlines, and the groundmass consists of a fine granular aggregate of quartz, tiny groups of slightly greenish radiating chalcedony crystals and elongated wisps of greenish-brown mica. The amount of mica varies with the constitution of the original rhyolite.

A more advanced stage of alteration is indicated by the stretching of quartz crystals, traces of whose original form may sometimes still be recognized (Fig. 3D). Although the central part of the stretched crystal is completely recrystallized, its fragmental terminations are optically continuous. Orthoclase has completely disappeared and biotite is replaced by elongated masses of magnetite dust amongst which a little micaceous material may sometimes be recognized. The groundmass consists of extremely fine material not unlike the cryptocrystalline base of the original rock, but differing from it in showing a well-marked schistosity instead of a fluidal fabric. The material of the groundmass appears to consist mainly of fibrous chalcedony or quartz. This rock, exhibiting evidence of intense crushing and shearing, closely approaches a *mylonite* (Lapworth, 1885; Crickmay, 1933).

Chemically these rocks occupy a position between the potash and soda-potash rhyolites (Hatch, 1889). The analysis compares fairly closely with a potash rhyolite quoted by Hatch (1914), but examination of numerous analyses (Washington, 1917) shows that the K_2O/Na_2O ratio is lower than that of most of the potash rhyolites, and in this respect the Bredbo rhyolite compares only with the other four rocks listed.

	I.	II.	III.	IV.	V.	VI.
SiO_2	75·66	76·4	79·21	74·73	74·30	77·46
Al_2O_3	14·42	14·2	9·93	10·82	13·77	9·36
Fe_2O_3	1·21	1·6	0·98	2·46	1·76	1·50
FeO	n.d.	—	tr.	0·58	0·30	0·85
MgO	0·59	—	0·40	0·20	0·85	0·12
CaO	0·09	0·6	0·10	0·80	0·30	0·17
Na_2O	1·34	1·8	2·05	2·68	2·71	1·36
K_2O	4·74	4·2	5·25	4·40	4·96	5·15
H_2O+	1·91	1·5	1·51	2·94	1·25	3·40
H_2O-	—	—	—	0·27	0·02	—
TiO_2	0·20	—	—	0·12	—	tr.
P_2O_5	0·11	—	—	0·12	0·20	—
MnO	n.d.	—	—	0·03	0·02	—
	100·27	100·3	99·43	100·15	100·44	99·37
Sp. Gr.	2·66	—	—	—	2·67	—

I. Rhyolite (slightly sheared). Travelling Stock Reserve, south of Bredbo. Anal. G. A. Joplin.
II. Potash Rhyolite. Tardree, Co. Antrim, Ireland. Anal. J. H. Player. F. H. Hatch, The Petrology of the Igneous Rocks, 1914, p. 262.
III. Rhyolite. Monte Tombalo, Kruzzino, Corsica. Anal. J. Deprat, *B. Sv. Ct. G. Fr.*, xvii, No. 117, 1907, p. 59. In W.T. No. 15, p. 56.
IV. Rhyolite Perlite. Waiau Valley, Aroha, Hauraki, New Zealand. Anal. Surv. Lab. Henderson and Bartrum, *N.Z. Geol. Surv.*, Bull. 16, 1913, p. 69. In W.T. No. 101, p. 72.
V. Quartz Porphyry. Muraunbach, Gotthard Massif, Bernese Alps, Switzerland. Anal. L. Hezner. In W.T. No. 78, p. 68.
VI. Quartz Porphyry. Leitimor, Ambon Island, Moluccas. Anal. O. Brunck. R. D. M. Verbeek, *Jb. Mijnw*, xxxiv, 1905, p. 85. In W.T. No. 28, p. 58.

Rhyolitic tuffs occur among the rhyolites and all gradations from an igneous rock to a crystal-tuff may be found. The same minerals are present, but quartz seems to be a little more abundant and the finer material of the base usually shows silicification. One specimen from the hill on the main road just south of Bredbo contains a tabular pseudomorph of what appears to have been an original plagioclase crystal. It consists of a fine aggregate of quartz and epidote and the recrystallized grains are so arranged that they suggest twin lamellae. Like the rhyolites with which they are associated, the tuffs have suffered varying degrees of dynamic metamorphism.

(iv). *Quartz-felspar-porphyries.*

These rocks show a good deal of variation in mineral composition and in degree of shearing, and at times they closely resemble certain of the rhyolites. The main distinction, however, is that plagioclase is an essential mineral in the porphyries and even in the most sheared rocks its former presence is revealed by masses of saussurite.

The quartz-felspar-porphyries contain larger phenocrysts than the rhyolites and these consist of corroded crystals of quartz (up to 6 mm.) and tabular crystals of both plagioclase and orthoclase. In a few specimens bleached or completely chloritized biotite phenocrysts with a puckered cleavage are present.

All specimens show evidence of dynamic metamorphism. Quartz and felspar phenocrysts are usually crushed and the cracks are infilled with minute grains of quartz or with a fine aggregate of quartz, chlorite and/or green mica. In some cases transverse cracks are developed in the larger felspar phenocrysts and optically continuous columnar quartz crystals have cemented the fragments giving the appearance of weaving. When fresh the plagioclase may show curved twinning lamellae. Occasionally both orthoclase and plagioclase are albitized.

The groundmass consists of sericite, fine granular quartz and sometimes elongated wisps of green mica. The constitution of the groundmass varies with the degree of shearing and with the composition of the original rock; thus under conditions of severe crushing a type originally rich in orthoclase shows crushed quartz and sericitized felspar in a sericitic groundmass, and a type originally rich in plagioclase shows much saussuritization of the phenocrysts and the development of epidote, albite and carbonates in the groundmass. An augen-structure is not uncommon.

A rock cropping out on the Adaminaby Road, near the 21-mile-peg in the Parish of Cosgrove, apparently occurs as a sill within the Coolringdon Beds which are here within the chlorite-zone. Though finer in grain, this rock shows affinities with the quartz-felspar-porphyries and may have been a smaller and more rapidly cooled intrusion. It contains corroded phenocrysts of quartz with undulose extinction and trails of fluid pores, and smaller phenocrysts of orthoclase and plagioclase. The phenocrysts form augen in a base of biotite, muscovite, and chlorite, the arrangement of which gives the rock a well-marked lepidoblastic structure. Micaceous bands often show a false-cleavage.

2. COOLRINGDON BEDS.

On the western limb of the anticline the Coolringdon Beds are well exposed west of Cooma (Joplin, 1942). They consist chiefly of psammites and siliceous pelites and occur in the zone of clastic mica and in the chlorite-zone. Although the typical black slates have not been found in the area to the north, similar psammites and siliceous pelites in the zone of clastic mica and in the chlorite-zone occur west of Murrumbucka where they may be followed for some distance along the Adaminaby Road until they finally disappear beneath basalt (Plate v). A small mass of sheared felsite closely resembling the quartz-felspar-porphyry of the Bransby Beds, occurs near the 21-mile-peg. This possibly represents a sill contemporaneous with the porphyries and has been described with them above.

As the psammites and siliceous pelites of the western limb resemble those already described in the zone of clastic mica in the southern part of the area about Cooma (Joplin, 1942), no further description is necessary. In this northern district the psammites of the Coolringdon Beds within the chlorite-zone are similar to those described from the Binjura Beds of the same zone at Cooma.

On the eastern limb the Coolringdon Beds crop out over a limited area south of Bunyan (Fig. 4). Here they are directly overlain by the Bransby Beds and consist of black and buff siliceous pelites with a few interbedded psammites. A progressive metamorphism may be traced in the siliceous pelites in an east-to-west section from the eastern side of the main Sydney Road to the outcrop of a tongue of Silurian gneiss, about 600 yards west. The least altered rock is a siliceous, carbonaceous type very similar to the more sericitic rocks already described from the western limb (Joplin, 1942, pp. 161–2). A part of the siliceous base, however, is recrystallized and forms small lenses of a fine quartz mosaic. Narrow quartz veins also traverse the rock. A slightly more altered rock occurs west of the road; this is more schistose and white mica occurs in slightly larger flakes. Types from the crest of the hill, a little further west, show a further advance in metamorphism. These rocks contain flakes of muscovite arranged around recrystallized lenticular patches of quartz, and a less psammitic type shows a well-marked schistosity with abundant white mica stained by iron oxides. Carbonaceous material forms minute flecks and may be graphite. Quartz veins commonly intersect these rocks and some of them carry limonitized pyrites. In the little hollow near the contact of the Silurian gneiss, Por. 60, Parish of Binjura, a rock of this type contains abundant white mica exhibiting plications, and the lenticular quartz mosaics are a little coarser in grainsize. A very similar, though coarser, plicated rock occurs on the hill behind Cooma Cemetery, Por. 319, Parish of Binjura. These rocks are essentially muscovite-schists. The initial composition of the siliceous pelites inhibits the formation of biotite and of andalusite in their respective zones, and as no aluminous pelites occur in the Coolringdon Beds, it is difficult to zone them accurately. It can be quite definitely stated, however, that on the east these beds attain a higher grade of metamorphism than they do on the west, and it seems probable that the plicated rock in Por. 60 is in the biotite-zone and the coarser one in Por. 319 in the andalusite-zone.

In 1914, Browne showed that there was a progressive metamorphism from graptolite-bearing slates into high-grade crystalline schists. Later work (Joplin, 1942) has pointed to the existence of an anticlinal structure with the graptolite-slates of the Coolringdon Beds overlying the more altered Binjura schists. Thus on the west, near the chlorite isograd, there is a lithological break, and on this evidence alone it might be argued that the progressive metamorphism from graptolite slate to schist is only apparent and that the break is an unconformity or disconformity with low-grade Upper Ordovician rocks laid down after the metamorphism of the schists. The occurrence of black slates in the high-grade zones on the east, however, shows that such is not the case, and that, though a lithological break occurs near the chlorite isograd, the progressive metamorphism is continuous. Thus Browne's later contention (1929) that the metamorphism is Ordovician is amply confirmed.

A psammite associated with the siliceous pelites on the western side of the road in Pors. 60/31 shows flakes of mica curved round lenses of a fine quartz mosaic. The mica is muscovite, green mica and a little incipient biotite. A similar rock, a little further south in Por. 58, consists of mica interleaved with a fine quartz mosaic and with occasional lenses of chlorite and green mica. These rocks are not unlike psammites from the biotite-zone or lower part of the chlorite-zone where they occur in the Binjura Beds on the western limb of the fold.

3. BINJURA BEDS.

In the earlier description of these beds (Joplin, 1942), it was stated that they consisted of an alternating series of psammites and pelites varying from bands several feet in thickness to seams only a fraction of an inch in width. It was shown by chemical analysis that the pelites are highly aluminous, and microscopic examination revealed that aluminous minerals were formed during metamorphism. Five rock types—namely, psammites with an argillaceous and with a tuffaceous matrix, aluminous pelites and banded and homogeneous psammopelites, have been traced through chlorite-, biotite- and andalusite-zones in the Cooma area and it has been shown that these rocks form the sedimentary foundation of the granitized rocks.

On the western limb of the fold, in the area north and north-east of Murrumbucka, all these types have been recognized and the continuation of the metamorphic zones has been plotted on the map (Plate v). The small-scale map (Fig. 4) shows that the chlorite-zone has now been traced for a distance of over 30 miles, whilst others have been followed for 20 miles and over. The permeation-zone, which corresponds very closely to the sillimanite-zone of the Scottish Highlands, is poorly developed in the north, but there are several reasons for this. Firstly, the Silurian gneiss is intrusive into much of the area where this zone would be expected to occur; secondly, the contact-effects of this intrusion have possibly obliterated recognizable outcrops of rocks belonging to this zone; and thirdly, compression may have been localized and not sufficiently great in the north to produce this high-grade zone. In Por. 77, Parish of Murrumbucka, east of the head of Pilot Creek, outcrops of the permeation-zone rocks are very typical and exactly similar to the type-section on Spring Creek, but along Pilot Creek itself, and elsewhere in the northern region, outcrops are not typical and have possibly suffered some alteration as a result of the Silurian intrusion.

In the earlier paper several zones were drawn on the eastern side of the Cooma gneiss within the Municipality of Cooma in the railway loop just north-east of the town. A tongue of Silurian gneiss invades these rocks and there is some evidence to show that types with the appearance of andalusite- or even of biotite-zone rocks were originally permeation-zone rocks that have suffered a low-grade "wet" contact-metamorphism. Thus a rock from the road cutting near the level-crossing about a mile north-east of the town consists of white mica, biotite and quartz and on mineralogical grounds would be placed in the biotite-zone. Closer examination reveals, however, that the biotite is a high-grade type and contains tiny quartz pellets that have been observed only in the higher grade rocks. Furthermore, psammopelites from nearby have suffered little later alteration and are typical of the andalusite-zone. In the railway cutting itself the presence of a tongue of gneiss has complicated matters considerably. The biotite of the psammites with a typical high-grade structure has been completely chloritized and pelites contain large blades of bluish-green pennine and/or muscovite. The presence of an occasional andalusite crystal and of a little carbonaceous material suggests that these were originally in the andalusite-zone.

It has been stated (Joplin, 1942) that the tuffaceous psammites occur high in the Binjura Beds as well as in lenticular masses on a slightly lower level. These rocks are met with in a similar position further north and it is now believed that they have a very limited vertical range (Fig. 1) and that, although they cannot be used strictly as a datum horizon, they may prove useful in elucidating the structure. No attempt has been made to map the area in such detail as to include small lenses of the Coolringdon Beds folded into the lower beds, but such a structure is suggested in the hypothetical sections (Fig. 5), and this is based on the occurrences of the tuffaceous psammite at intervals east of the main western boundary of the Coolringdon Beds.

Basic granulites, possibly representing small basalt flows near the base of the Binjura Beds (Fig. 1), occur as inclusions within the Cooma gneiss in the town of Cooma. These are to be found on approximately the same line of strike in the northern area, where they occur as inclusions within the Silurian gneiss.

4. ORDOVICIAN INTRUSIVES.

(i). *Cooma Gneiss and Acid Phases.*

Reference to the map (Plate v) will show that an elongated strip of Ordovician gneiss, 5 miles in length, crops out about 6 miles north of the main mass of Cooma gneiss, and as previously mentioned (Joplin, 1942, p. 186), Browne has found inclusions of it within the Silurian gneiss as far distant as 30 miles north of Cooma. Though surrounded by the Silurian gneiss in the northern part of the area, it is little affected by contact-alteration. It is here represented by the plagioclase-poor type of Cooma gneiss.

Certain small areas of a fine-grained acid gneiss occur near the southern end of the Silurian gneiss east of Pilot Creek, and in isolated outcrops west of Murrumbucka Creek above the mouth of Long Creek. In handspecimen these closely resemble the fine-grained muscovite-rich type of Cooma gneiss, but for reasons discussed below it is believed that they represent a phase of the Silurian gneiss and are described as such (p. 173).

The dykes of graphic pegmatite, so common near Cooma, have not been encountered in the northern area.

(ii). *Amphibolites.*

The basic intrusives represented by amphibolites in the neighbourhood of Cooma (Joplin, 1939, 1942) also occur in the north where they have been engulfed by, and partly assimilated by, the Silurian gneiss. These rocks, as well as the basic granulites from the Binjura Beds, are together responsible for the basification of the Silurian gneiss, and though this is referred to again in connection with the hybridization of the gneiss, it is dealt with very briefly. At Cooma the amphibolites have been engulfed by the Ordovician gneiss and their reaction with it was the subject of a separate communication (Joplin, 1939), so it is hoped that later a more detailed study of their relation to the Silurian gneiss may be made along the same lines.

The ultrabasic chlorite-amphibolites that occur at Cooma have been found in the northern area only at one point, along the northern boundary of Por. 79, Parish of Murrumbucka.

IV. SILURIAN INTRUSIVES.

1. QUARTZ-DIORITE-PORPHYRITE.

Browne (1943) has noted several collinear lenses of "granite-porphyry" extending intermittently from north of Colinton to near the mouth of the Umaralla River. Their composition suggests their relation to the Murrumbidgee Bathylith and it is probable that they are a forerunner of it.

In handspecimen the rock is markedly porphyritic with phenocrysts of quartz, felspar and a ferromagnesian mineral in a fine crystalline groundmass. Quartz phenocrysts often measure up to 9 mm. and are very conspicuous on weathered surfaces. A slight schistosity is developed in the two most southerly lenses and the rocks closely resemble certain phases of the Ordovician quartz-felspar-porphyries that have suffered shearing.

Under the microscope the phenocrysts are seen to consist of subidiomorphic and much corroded crystals of quartz and tabular crystals of saussuritized andesine. In some of the least altered types small subidiomorphic crystals of hornblende occur as phenocrysts and these show marginal resorption. In most rocks, however, masses of chlorite, epidote and sphene represent completely resorbed hornblende crystals. Some types contain phenocrysts of biotite usually altered to chlorite. Occasional crystals of apatite measure up to ½ mm. In the more stressed rocks, to the south, carbonates are well developed and often fill cracks in, or form elongated rods at the terminations of, crushed quartz phenocrysts. Quartz shows undulose extinction.

The groundmass of the least altered types consists of an allotriomorphic granular aggregate of quartz, sericitized plagioclase, chloritized hornblende and biotite and sometimes a little orthoclase. Tiny quartz grains about the margin of the quartz phenocrysts are often optically continuous with the larger crystal, and this suggests the marginal indentations sometimes associated with recrystallization of the groundmass. The sharp boundaries of most phenocrysts, however, indicate that if such recrystallization has taken place it could have been only very slight. In the more stressed types wisps of chlorite and elongated grains of epidote and carbonates are abundant.

In view of the abundance of plagioclase and of the occurrence of hornblende, the rock appears to be an intermediate type, and its apparent relation to the blue gneiss (quartz-diorite) suggests that it was originally a quartz-diorite-porphyrite.

2. MURRUMBIDGEE BATHYLITH.

Only the forked southern extremity of the Murrumbidgee Bathylith (Browne, 1943) crops out in the present area of investigation. The most westerly prong extends from near the junction of Murrumbucka and Long Creeks to the head of Pilot Creek, a distance of some 6½ miles. It is about 2 miles wide at its northern end and tapers to less than ½ mile where it finally frays out into several small tongues interdigitated with the granitized schists.

The easterly prong maintains a fairly uniform width of from 2 to 3 miles over a distance of 8 miles and then splits into two narrow tongues 3 miles apart. The most westerly of these extends for 5 miles from Butler's Creek across the Mittagang Road and railway loop north-east of Cooma Station and is lost beneath basalt in the railway goods-yard. This apophysis will be referred to as the middle tongue. The most easterly tongue extends from just north of Bunyan and disappears beneath basalt about 1 mile further south.

Small outcrops of a very acid gneiss occur at intervals near the margin of the westerly prong of the bathylith. They are particularly numerous near its southern extremity above Pilot Creek and on its western margin between Bark Gunyah and Long Creeks. This acid type closely resembles the Cooma gneiss and indeed may be of Ordovician age, but for reasons discussed below (p. 173), it is described here as a member of the Murrumbidgee Bathylith. Browne (1914, p. 184) has described acid gneisses, which he has called the pink and white gneisses, occurring on the eastern margin of the easterly prong.

(i). *Blue Gneiss* (*Quartz-diorite*) *and Associated Hybrids.*

Browne (1914) has applied the name "blue gneiss" to the normal rock comprising the southern part of the bathylith. In this earlier paper he was dealing mainly, as I am now, with the southern extremity of the bathylith where gneissic structures are pronounced, so the earlier descriptive name of "blue gneiss" has been retained. About Murrumbucka Gap the rock is a coarse black and white or bluish gneiss which weathers into characteristic elongated boulders dipping to the east. Further north Browne (1943) records a westerly dip. As in the case of the Cooma gneiss, large masses of quartz (up to 1 in.) and sometimes of felspar may occur.

Two types of gneiss may be distinguished, one particularly rich in biotite and containing no hornblende, the other containing both ferromagnesian minerals. These two types will be described together, as apart from the presence of hornblende and the greater proportion of dark minerals in the more basic type, there is no essential difference between them.

The rocks are slightly porphyritic with somewhat rounded phenocrysts of andesine ($Ab_{53}An_{47}-Ab_{55}An_{45}$) measuring about 5 mm. and occurring in a groundmass of quartz, andesine ($Ab_{65}An_{35}-Ab_{62}An_{38}$), hornblende and/or biotite with accessory sphene, apatite, pyrites and magnetite. In some varieties well-formed crystals of primary epidote are abundant. Most of these rocks show a well-marked banding which is particularly pronounced in the biotite-rich types where the mica gives a parallel structure or is wrapped round groups of phenocrysts to give a kind of phacoid structure. In places, usually near the margin, the rock almost resembles a schist and the groundmass consists of a mosaic of tiny interlocking grains. Sericite is abundant in some of these more stressed types.

Rocks containing biotite and epidote and usually a little hornblende occur in the wider part of the bathylithic tongues and in an area north of the region shown in the present map. These possibly represent a more basic phase of the magma, which under normal conditions would have crystallized as biotite-diorite, but which under conditions of piezo-crystallization (Weinschenk, 1916) gave rise to biotite-epidote-gneiss.

These rocks gradually give place to more massive and more basic types very rich in hornblende. Biotite and quartz are still present, though often subordinate, and the rock is obviously a more basic type that has crystallized without being subjected to much stress. The basicity may be due either to normal crystal differentiation or to assimilation. At the Gap Road crossing on Murrumbucka Creek, and further north on Spring Vale Creek numerous basic inclusions, mainly of amphibolite, occur in the blue gneiss, and it seems almost certain that some of the more basic types of gneiss are hybrids. Until detailed work has been done on the reactions between the amphibolite and the gneiss and until the whole of the bathylith has been examined, it is impossible to say how far differentiation or assimilation is responsible for the development of the more basic types.

Analysis I below represents a biotite-bearing rock free from hornblende, and although there is no specimen available of the other analysed rock (Anal. V) the chemical composition suggests a hornblende-biotite type.

	I.	II.	III.	IV.	V.	VI.	VII.	VIII.
SiO_2	63·35	64·04	66·06	64·61	64·43	64·78	64·25	62·10
Al_2O_3	16·92	15·58	15·25	16·14	18·61	17·45	19·30	16·03
Fe_2O_3 ..	1·23	0·80	1·10	2·15	1·52	1·53	1·70	2·55
FeO	4·58	4·47	3·69	2·61	2·14	2·35	3·64	1·95
MgO	3·03	2·64	2·27	2·41	2·13	2·04	2·06	2·67
CaO	4·45	3·52	4·86	5·07	5·20	4·07	4·20	6·05
Na_2O	1·90	2·42	2·16	2·59	2·47	3·12	2·71	3·12
K_2O	2·28	2·80	2·77	1·72	1·87	1·83	1·42	1·48
H_2O+ ..	0·86	2·25	0·94	2·18	1·06	1·97	0·37	1·70
H_2O- ..	0·09	0·38	0·30	0·07	0·26	—	—	1·07
TiO_2	0·84	0·80	0·70	0·46	0·10	1·07	0·32	0·71
P_2O_5	tr.	0·18	0·11	0·40	0·11	—	0·12	0·14
MnO	—	tr.	0·02	0·08	—	0·03	—	tr.
Etc.	—	—	0·28	0·05	—	0·13	—	0·09
	99·53	99·88	100·51	100·54	99·90	100·37	100·09	99·66
Sp. Gr. ..	2·75	2·722	2·726	—	—	—	—	2·565

I. Quartz-mica-diorite (hornblende-free). Murrumbucka Gap, Por. 46, Par. of York. Anal. G. A. Joplin.
II. Granodiorite. Braemar House, Macedon, Victoria. Anal. R. J. Lewis. Skeats and Summers, *Geol. Surv. Vict.*, Bull. 24, 1912, p. 20. In W.T. No. 79, p. 368.
III. Dacite. Wombeyan Road, Wollondilly River, N.S.W. Anal. J. C. H. Mingaye. G. W. Card, *Rec. Geol. Surv. N.S.W.*, viii (3), 1907, p. 261. In W.T. No. 77, p. 368.
IV. Quartz-mica-diorite Gneiss. Ensay, N.E. Victoria. C. M. Tattam, *Geol. Surv. Vict.*, Bull. 52, 1929, p. 38.
V. Quartz-diorite. Cooma. Anal. E. A. Burnard and E. T. Wallace. W. R. Browne, personal communication.
VI. Diorite-porphyrite. Hauzenberg, Bayrischer Wald, Bavaria. Anal. G. Vervnert. A. Frentzel, *Geogr. Jhft.*, xxiv, 1911, p. 166. In W.T. No. 70, p. 263.
VII. Cordierite Micronorite (Inclusion in Andesite). Mont Pelée, Martinique, West Indies. Anal. A. Pisani. A. Lacroix, Mont Pelée, 1904, p. 550. In W.T. No. 107, p. 385.
VIII. Andesite, Copper Island, Commander Islands, Bering Sea. Anal. Z. Starzynski. Z. Starzynski, *B. Ac. Sc. Crac.* Ser. A, 1912, p. 659. In W.T. No. 204, p. 397.

(ii). *Acid End-phases.*

(*a*) *White Gneiss.*—As indicated by Browne (1914, p. 184) these rocks occur in an elongated mass on the eastern margin of the blue gneiss. The most southerly outcrop occurs just south of Cooma Creek near Bunyan and Browne (1931) has traced them north for a distance of some 40 miles.

In handspecimen the rock is a well-foliated gneiss consisting of quartz, felspar and a little mica, and with an increase of mica and a decrease in the lighter constituents, it passes into the blue gneiss, all transitions being apparent in the field.

Under the microscope mortar structure is well exhibited with microcline porphyroclasts set in a fine mosaic of quartz, felspar and mica. The porphyroclasts (3 mm.) are somewhat elongated and their longer axes are usually roughly parallel. The mosaic is very variable in grainsize with single grains of quartz, microcline or plagioclase varying from 1 mm. to less than 0·1 mm. Occasionally small groups of grains measure about 1 mm. Muscovite, with a little biotite, occurs in elongated flakes arranged in narrow bands. A little finely-divided carbonaceous material is sometimes present. This possibly represents an undigested remnant of the Coolringdon black slates, which the white gneiss has invaded. The composition of the slate is such that all other mineral constituents would be in phasal equilibrium with the magma, and therefore completely resorbed.

A type from the Murrumbidgee gorge in Por. 13, Parish of Bransby, has a little less prominent mortar structure and a more uniform grainsize. A little granular epidote is associated with green and white mica, and most of the minerals form elongated grains arranged in parallel bands.

Certain gneisses have a definite pink colour, though in texture and mineral composition they resemble the white gneiss and are closely associated with it in the field. The potash felspar of these gneisses is extensively sericitized and kaolinized and it is believed that they are hydrothermally altered phases, the alteration having taken place at the time of the injection of the pink gneiss.

It seems evident that an easterly-directed pressure was responsible for squeezing out an acid liquid fraction during the end-phase of consolidation of the bathylith. The rounded phenocrysts in the blue gneiss suggest that this pressure-differentiation took place before the complete consolidation of the rock (Barrow, 1892; Harker, 1932). This pressure either persisted or recurred after the consolidation of the white gneiss. The mortar structure suggests a recurring stress.

The analysis of a typical white gneiss is given below.

	I.	II.	III.	IV.	V.	VI.	VII.
SiO_2	74·99	74·82	73·70	76·26	77·09	76·10	75·6
Al_2O_3	5·58	13·63	13·60	12·06	13·04	13·45	13·2
Fe_2O_3	10·44	0·97	0·56	1·14	0·82	1·34	1·3
FeO	n.d.	0·83	1·76	0·66	0·26	n.d.	n.d.
MgO	0·09	0·08	0·36	0·06	0·12	0·61	0·6
CaO	0·50	0·87	0·96	0·69	0·63	0·42	0·6
Na_2O	2·66	3·03	2·64	2·89	3·11	2·55	2·5
K_2O	4·82	4·81	4·31	4·50	4·50	5·01	5·4
H_2O+	0·52	0·82	1·22	0·71	0·07	1·00	1·0
H_2O-	0·17	—	—	—	0·03	—	—
TiO_2	tr.	—	—	0·40	0·05	—	—
P_2O_5	n.d.	—	0·30	—	0·10	—	—
MnO	tr.	—	—	0·25	tr.	—	—
C	p.n.d.	—	—	—	—	—	—
	99·77	99·86	99·41	99·62	99·82	100·48	100·1
Sp. Gr.	2·62	—	2·672	—	2·600	—	—

I. White Gneiss. Cutting on Sydney Road, Bunyan. Anal. G. A. Joplin.

II. Granite. Staudenbuhl, n. Heiligkreuz, Baden. Anal. Beckmann. K. Futterer, *Mt. Bad. G.L.-A.*, II, 1893, 41. In W. T. No. 64, p. 69.

III. Granite. Platten, Bohemia. Böttger, *Mt. Phar. Inst. Erl.*, 1889. In W.T. No. 72, p. 69.

IV. Granite Porphyry. Sundsvall, Rödö, Sweden. Anal. Santesson. P. J. Holmquist, *Afh. Sv. G. Und.*, No. 181, 1899, 45. In W.T. No. 57, p. 67.

V. Granite. Sheppard Creek, Rossland District, British Columbia. Anal. M. F. Connor. R. A. Daly, *Can. G. S. Mem.*, 38 (1), 1912, 355. In W.T. No. 24, p. 63.

VI. Porphyry. Marcillat, La Creuse, France. Anal. Pisani. L. de Launay, *B. Sv. Ct. G. Fr.*, xi, No. 83, 1902, 76. In W.T. No. 38, p. 65.

VII. Microgranite. Genis, Correze, France. Anal. J. de Lapparent. J. de Lapparent, *B. Soc. Min. Fr.*, xxxii, 1909, 267. In W.T. No. 43, p. 65.

(*b*). *Pink Gneiss.*—These rocks vary from massive coarse red granites containing patches of greenish-yellow epidote to well-foliated pink gneisses consisting of quartz, pink felspar and narrow bands of chloritized biotite. The massive varieties usually occur as dykes whilst the foliated type is closely associated with, and often appears as a border phase of, the white gneiss.

Under the microscope the massive rock is seen to consist of large allotriomorphic grains of quartz, microcline and a much altered plagioclase which appears to have been albite. The selective alteration of the felspars is very striking. Microcline is mainly fresh, though there may be small patches of sericitization particularly along the cleavages. Adjacent grains of plagioclase are completely pseudomorphed by masses of sericite, kaolin, small granules of epidote and/or clinozoisite and sometimes a little calcite. A little greenish biotite is usually present and sometimes larger independent grains of epidote occur. Quartz-epidote veins are often associated and a slight mortar structure is occasionally developed.

The foliated pink gneisses are hydrothermally altered white gneisses rather than true pink gneisses that are characterized by the presence of altered plagioclase.

It seems likely that after the differentiation of the Murrumbidgee Bathylith and the squeezing out of an acid phase under stress, there was a waning of stress which recurred to impose a foliation upon the white gneiss and again died away before the consolidation of the pink gneiss. Thus the pink gneiss, with its massive structure and dyke-like occurrence, indicates a period of tension at the close of the Silurian diastrophism.

(*c*). *Fine-grained Muscovite Gneisses.*—These rocks occur in numerous small, isolated outcrops close to the margin of the most westerly prong of the blue gneiss in the Parishes of Murrumbucka and York. They appear to be associated only with this prong of the bathylith and are developed most abundantly near its southern extremity, above Pilot Creek, and in the hilly country west of Murrumbucka Creek between Bark Gunyah and Long Creeks.

The origin of these rocks is most puzzling, for in the field they closely resemble the fine acid phase of the Cooma gneiss (Joplin, 1942, p. 187) and indeed may be related to it. Nevertheless, although their proximity to the prong of blue gneiss may be fortuitous, there are some mineralogical reasons for assuming that they are related to the Silurian intrusives.

Under the microscope there is some variation in texture, but they are mostly fine-grained massive rocks, sometimes with a slight mortar structure, consisting of quartz, plagioclase, microcline, muscovite and brown biotite with occasionally a little myrmekite, apatite and tourmaline. The brown biotite, particularly when it contains inclusions of zircon, resembles that of the Ordovician gneiss, but these rocks differ from the normal Cooma gneiss in that they contain no andalusite or sillimanite and from the fine-grained acid phase of it in that they contain microcline and abundant plagioclase. The presence of these minerals indicates affinities to the blue and white gneisses although it is true that the Ordovician graphic pegmatites contain albitized microcline. In the field, however, there is no similarity between these fine-grained gneisses and the graphic pegmatite and they resemble only the fine-grained phase of the Cooma gneiss to which they appear to be mineralogically dissimilar.

(*d*). *Tourmaline Pegmatites and Schorls.*—Small dykes, veins and irregular masses of tourmaline pegmatite and schorl are numerous about the most westerly prong of the bathylith, and slight tourmalinization of the schists has been noted at the extremity of the middle prong near the railway loop.

The dykes are of small dimensions and, except for a graphic schorl near Murrumbucka Gap, no graphic structures have been observed and they are quite unlike the Ordovician pegmatite dykes. The most common occurrence of this type is in small irregular masses near the margin of the gneiss. Such masses occur near the Gap Road in Por. 64, Parish of Murrumbucka, and above Pilot Creek in Por. 122, Parish of Murrumbucka. The rocks are very coarse grained, and fractured tourmaline crystals healed with quartz may measure over an inch in length and nearly half an inch in diameter.

In the immediate neighbourhood of these masses the acid gneisses contain tourmaline, and this seems to indicate that the tourmaline-bearing solutions were the last phase of the magma which was beginning to be precipitated when the acid gneisses were consolidating, but which was finally precipitated in intrusive veins.

V. CONTACT-AUREOLE OF THE MURRUMBIDGEE BATHYLITH.

In mapping the northerly extension of some of the Ordovician metamorphic zones certain peculiarities, anomalies and deviations from type were met with, and these can only be ascribed to a later, superimposed contact-alteration by the Silurian gneiss. A contact-aureole about the Murrumbidgee Bathylith has been sketched (see Plate v), but actually the mapping of such an aureole in the field is almost impossible as there are such wide differences in the contact-effects upon the rocks of the various metamorphic zones. Furthermore, it is shown below that certain volatiles have been concentrated in the separate prongs of the bathylith and that these are responsible for slightly different types of metamorphism. Thus the plotting of the contact-aureole about the Silurian gneisses has been based largely upon microscopic work.

Reference to the map (Fig. 4) will show that within this area the bathylith invades Binjura, Coolringdon and Bransby Beds, but that the greater part of it occurs within the Binjura Beds. Further, it will be seen that within these beds rocks of the injection-, permeation-, andalusite- and possibly of the biotite-zone have been affected.

Near the head of Long or Barkersdale Creek, rocks that have suffered a contact-alteration are mainly psammites, and owing to their initial composition it is difficult to say whether they were originally within the biotite-zone. Downstream, partly hornfelsed rocks of the andalusite-zone are abundant. In these rocks andalusite is well developed and usually forms larger grains or granular patches than it does in the normal andalusite-schists. Furthermore, the schistosity of these rocks is not so well marked and there is some evidence of hornfelsing. Some of the rocks on Long Creek are very similar to the contact-altered pelites just within the margin of the permeation-zone in the southern area (Joplin, 1942, p. 169 and Figs. 7A and 7B). Like these types, they contain a good deal of white mica, but are perhaps even richer in this constituent, and the associated psammites show evidence not only of hornfelsing, but also of greisenization.

Near the mouth of Long Creek, close to the boundary of the blue gneiss and in the vicinity of one of its more acid phases, a psammitic rock shows granitization and slight *lit-par-lit* injection, but this is quite local and appears to be associated with the acid, tourmaline-bearing gneiss. Another such occurrence crops out in the bed of Bark Gunyah Creek in Por. 89, Parish of Murrumbucka, and here again granitization appears to be confined to the psammitic rocks. In the field it was at first thought that these masses represented remnants of the Ordovician injection-zone, but closer examination both in the field and in the laboratory has convinced me that they are merely andalusite-zone psammites affected by the Silurian gneiss.

On some of the smaller creeks between Long and Bark Gunyah Creeks tiny ptygmatic veins of quartz and quartz-felspar invade the schists, but the effect of such "granitization" is by no means widespread and does not appear to have affected the body of the invaded rock.

On Pilot Creek the blue gneiss enters the permeation-zone and it is here that mapping has been most difficult. As aforementioned (p. 168) mottled gneisses and corduroy granulites, exactly similar to those of the type-area on Spring Creek, occur in Por. 77, Parish of Murrumbucka, but to the south and to the west these give place to rocks that are by no means typical and appear not unlike some of the granulites of the injection-zone, although very little magmatic material is present and this is represented only by small veins and occasional *lits* of quartz and quartz-felspar. Under the microscope they are seen to have a granoblastic structure, though a slight schistosity and sometimes a sedimentary banding may still be preserved. Andalusite, muscovite and reddish-brown biotite are abundant and cordierite and sillimanite not infrequently present. The amount of quartz varies with the initial composition of the rock and a little felspar is sometimes present.

Within the injection-zone no distinction can be made either in the field or in the laboratory between rocks granitized by the Cooma gneiss alone or altered by both Ordovician and Silurian gneisses.

The middle prong of the Silurian bathylith invades both andalusite- and permeation-zone rocks along the Mittagang Road and in the railway loop just north-east of Cooma

Railway Station, and it is here that the alteration has been most intense. The permeation-zone rocks have been much greisenized and often appear to be comparatively low-grade schists, while rocks of the andalusite-zone have been both greisenized and chloritized and often contain large blades of muscovite and bluish-green pennine. The biotite of the associated psammites is also completely chloritized, although the original high-grade structure of the rock is still preserved.

On Butler's Creek and on the Mittagang Road a peculiar rock occurs associated with the middle prong of the gneiss. Unfortunately its outcrop is such that its relation to the gneiss cannot be examined, but certain intermediate types suggest that it is in some way genetically connected with the gneiss. It is a coarse-grained rock that in handspecimen appears to consist almost exclusively of mica. Under the microscope, however, quartz and felspar are seen to be present in addition and sometimes long blades of bluish-green chlorite occur. The bulk of the mica is muscovite clouded with sillimanite needles, but some rocks contain appreciable quantities of biotite and these types appear to be closely related to the blue gneiss. Read (1931) has described rather a similar rock occurring in a vein at Learable Hill, Central Sutherland.

The Coolringdon Beds come within the aureole of both the middle and most easterly prongs of the bathylith. Near Cooma Cemetery these rocks occur within the andalusite-zone and the only noticeable effect of the Silurian gneiss on them is a slight introduction of tourmaline. Near Bunyan, in the vicinity of the white gneiss, black slates, probably within the biotite-zone, show silicification, and veins of quartz and limonitized pyrites sometimes occur.

The eastern margin of the eastern prong is adjacent to the Bransby Beds and these have been slightly affected in a number of ways. Pure limestones have recrystallized or have been silicified or epidotized, whilst impure ones have developed tremolite, diopside and epidote. Tuffs and slates have been impregnated with pyrites and the rhyolites show some evidence of weak contact-metamorphism. The quartz-diorite-porphyrite which was apparently a forerunner of the Silurian bathylith also shows some signs of contact-metamorphism.

To recapitulate, the metamorphism due to the Silurian intrusions is mainly weak and differs slightly in different parts of the bathylithic margin. Thus in the wider part of the intrusion near Long Creek, thermal effects are more noticeable and granitization slightly apparent, whilst further south, near the extremity of the tongues, volatiles have played a more important part.

Granitization and tourmalinization are prominent within the aureole of the western prong and these again, together with the development of chlorite in rocks of appropriate composition, are a marked feature of the contact-aureole of the middle prong. It was suggested before (Joplin, 1942, p. 169) that the presence of large blades of muscovite in some of the schists in the railway loop might be attributed to the fixation of sedimentary alumina by magmatic potash emanations.

The eastern tongue at the margin of the pink and white gneisses is characterized more by silicification of the surrounding rocks and the introduction of epidote and pyrites. On the east, tourmaline is absent.

Although the aureole of the Silurian bathylith is studied only in a very small area where it borders only the southern extremity of a very large intrusion, certain generalizations can be made concerning it. Thus it can be stated that thermal effects in the region of the tongues are negligible and that volatiles have played an important part in the apparent lowering in grade of the surrounding high-grade schists. Further north, where the bathylith begins to widen out, thermal metamorphism is more evident, but it appears to be of a somewhat low grade "wet" type.

VI. ASYMMETRY OF THE ORDOVICIAN METAMORPHIC ZONES.

1. THE PROBLEM.

Reference to Plate v and Fig. 4 will show that on the east, the Silurian gneiss separates the injection-zone from the chlorite-zone by a distance of less than one mile, and that on the west these two zones, about 3 miles apart, are separated by several other zones of varying degrees of metamorphism. This anomaly, together with the occurrence of permeation-zone rocks along Cooma Creek near Bunyan and their apparent discontinuation to the north, suggests the possibility of overthrusting.

Closer examination of the country immediately north-east of Cooma, however, has led me to the conclusion that the eastern zones are extremely narrow and that instead of

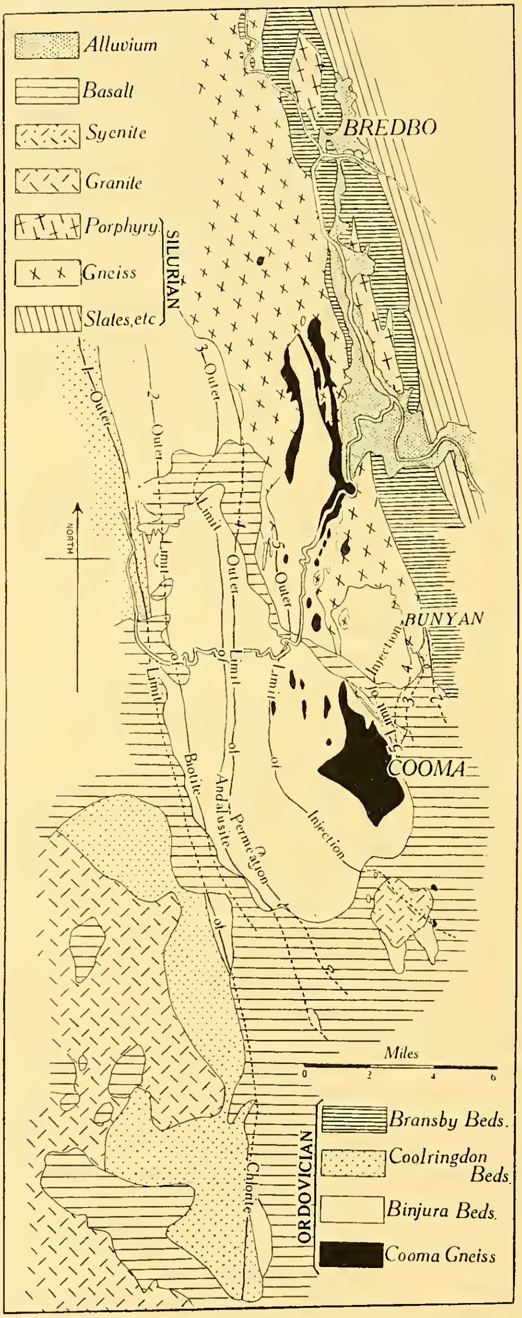

Fig. 4.—Sketch-map of Cooma Region showing outcrops of Binjura, Coolringdon and Bransby Beds and asymmetrical arrangement of metamorphic zones about Cooma gneiss. The boundary between the Binjura and Coolringdon Beds is only approximate, but its trend suggests that the Ordovician anticline is pitching to the S.S.E.

the injection-zone being thrust over the chlorite-zone, as was at first supposed, all the intermediate zones are present within a belt less than a mile in width and are now engulfed by the Silurian gneiss. Nevertheless, the zoning north-east of Cooma is by no means clear and the zones cannot be traced as they were on the west. Some of the difficulties in tracing and separating the eastern zones are listed below.

2. MAPPING DIFFICULTIES.

Basalt covers much of the area between Cooma and Bunyan and where the schists are exposed they usually occur in poor, isolated outcrops either on flat ground, as north of the railway loop, or in little gullies or breakaways in the basalt.

It has already been shown that the schists in the railway loop north-east of Cooma and on the first hill on the Sydney Road, just past the railway crossing, have been metasomatized as a result of their contact with a tongue of blue gneiss. In the field, high-grade rocks often appear to be of comparatively low grade and sometimes it is only careful microscopic study that reveals original high-grade structures. Nevertheless, some of the rocks can be definitely zoned in the field, but the zones cannot be followed for any distance owing to the scarcity of outcrops and the covering of basalt.

On the western margin of the eastern tongue the zoning is further confused. Just north-west of Bunyan, near the western margin of the white gneiss, a small mass of siliceous schist occurs. This appears to be a siliceous pelite of Coolringdon-type in the andalusite-zone, but less than 20 yards to the west Binjura rocks appear to be in the injection-zone. This may be due to slight overthrusting or to a superimposed Silurian metamorphism. It is possible that this locality marks the boundary between the Coolringdon and Binjura Beds and that the latter were originally in the permeation-zone and have been subsequently granitized by the blue gneiss. Elsewhere along the bathylithic margin, however, granitization is not well marked and appears to be confined only to the psammitic rocks. At this locality aluminous pelites are affected by granitization and the abrupt change from injection-zone to andalusite-zone certainly suggests local overthrusting. If such be the case, then the boundary between the Binjura and Coolringdon Beds here is a faulted junction.

Even when allowance is made for all these possibilities, however, it seems clear that the eastern metamorphic zones are much narrower than those of the west and the possible reasons for such a marked lack of symmetry must now be examined.

3. EXPLANATION OF THE ASYMMETRY.

The injection-, permeation- and andalusite-zones are unquestionably related to the Cooma gneiss (Joplin, 1942), but the relation of the biotite- and chlorite-zones to the igneous body is doubtful. Nevertheless, it is significant that, like the first three zones, there is a decrease in the width of the biotite-zone on the east; and any explanation for such a decrease must apply to all zones with the exception of the chlorite-zone whose width on the east is unknown. It seems reasonable to assume therefore that the Cooma gneiss invaded a terrain already in the chlorite-zone of regional metamorphism and that its contact-aureole extends out as far as the biotite isograd (see Fig. 5).

In studying the argillaceous rocks of Dutchess County, Barth (1936) recognized three facies, (1) muscovite slate facies, (2) cyanite schist facies, and (3) sillimanite gneiss facies, and he concludes "that, during the period of orogenesis, the sediments were heated and stewed in liquids of magmatic and anatectic origin, which reacted with the sediments and metasomatically transformed them into well-defined types of schists and gneiss". In discussing the matter further he states: "undoubtedly, the composition and amount of this liquid (i.e., the anatectic pore liquid) changes with the distance from the magmatic intrusions; the further away, the more attenuated the magmatic component and the smaller the deliquesced fraction of the pre-existing rocks".

With regard to the Cooma metamorphism, there is no doubt that magmatic material invaded the injection-zone, and it has been shown that the permeation-zone, though it has acquired little from the magma, has been soaked and permeated with magmatic fluids. This zone closely corresponds to the sillimanite-zone of the Scottish Highlands and there is no doubt that both high temperature and strong compression were mainly responsible for its formation, but there is nevertheless evidence that magmatic fluids have played a part—possibly as catalysts. It was shown (Joplin, 1942) that a little albite has been introduced into the rocks of this zone, but the time when this occurred is doubtful and it may have taken place after the main compression and permeation and when the magma had become sufficiently differentiated to form a sodic fraction.

The andalusite-zone appears to be a weak thermal aureole superimposed upon rocks that had already acquired a schistosity and there is no evidence of the influence of magmatic fluids.

If the biotite-zone is to be regarded as a part of the aureole of the Cooma gneiss, then it must have been caused either by far-reaching fluids or by an increase of temperature due to the igneous body. In either case the well-marked schistosity must have been acquired earlier. In a normal thermal aureole the outer zone is often marked by the development of biotite which forms at a lower temperature than the andalusite characterizing the inner zone of hornfelses (Tilley, 1924*a*). Thus it is possible that the biotite-zone represents the outermost part of the aureole where an increasing temperature, due to the Cooma gneiss, caused the formation of biotite in the chlorite-schists.

The chlorite-zone may be a still weaker and more remote ring but, as suggested in Table 1, the metamorphism may be purely dynamic and represent the first phase of the Ordovician diastrophism.

So far as the zones related to the intrusion are concerned, three possible explanations suggest themselves as the reason for the marked difference in width between the eastern and western zones. First, the inclination of the margin of the intrusive body may be steeper on the east; second, the rocks on the west may have been more susceptible to metamorphism both on account of their composition and as a result of their structure and dip; and third, solutions may have been driven out only in a westerly direction by a pressure directed from the east. Actually more than one cause has probably contributed.

The occurrence of small outcrops of Cooma gneiss on the Dairyman's Plain, west of the main mass, and of a small patch of injection-zone rocks among those of the permeation-zone near Pine Valley suggests that cupolas of the gneiss extended well west of the main outcrop. This, however, does not necessarily imply a more gentle inclination of the igneous body on the west. The prevailing easterly dips of the schists and the apparent concordant relation of the igneous rock suggest a steeply-dipping tabular body inclined to the east as shown in the hypothetical sections (Fig. 5). The inclination of the intrusive body therefore seems to be unrelated to the asymmetry of the zones.

Although reversals of dip sometimes occur, the Ordovician rocks have a prevailing dip to the east and any fluids escaping from the magma would find easier access in a westerly direction along the bedding planes than in an easterly direction across them. Furthermore, the magma appears to have been injected fairly close to the eastern boundary of the Binjura and Coolringdon Beds and near where these latter are thinning out and giving place to the Bransby Beds. Reference to Fig. 1 will show that the Binjura Beds are very largely aluminous pelites and these are not only remarkably susceptible to metamorphism but their well-developed schistosity facilitates the passage of magmatic fluids. The Coolringdon Beds on the other hand are mainly siliceous pelites and psammites largely composed of quartz. These rocks do not develop such a perfect cleavage and metamorphic changes are less profound owing to their composition. Tilley (1924*b*) has pointed out that a rock "originally composed of degradation minerals . . . accommodates its mineral composition to the impetus of rising temperature, whilst . . . a high-grade facies (igneous rock) is only partly converted". The Binjura and Coolringdon Beds are composed of degradation minerals, but it has been shown that the latter consist mainly of quartz, a circumstance which would make their behaviour under conditions of metamorphism somewhat comparable to that of an acid igneous rock. Furthermore, the Bransby Beds are largely composed of rhyolites, porphyries and crystal-tuffs and their mineral content is thus comparable to a high-grade metamorphic rock of similar chemical composition. Any metamorphism imposed upon them would necessarily result in very slight mineralogical changes and the alteration would be more of a structural character.

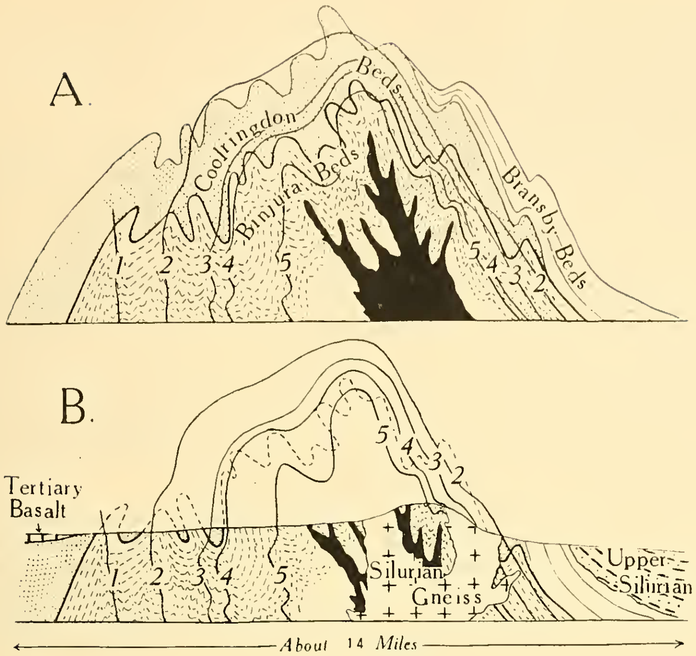

Fig. 5.

A.—Hypothetical section of Ordovician anticline showing prevailing easterly dips. The Bransby Beds on the east are shown to overlap the Coolringdon Beds which thin out on the east and are separated from the underlying Binjura Beds by a narrow zone of tuffaceous psammites. The Binjura Beds are invaded by a concordant intrusion of Cooma gneiss and various metamorphic zones are drawn about this—thus 1 = outer limit of chlorite, 2 = outer limit of biotite, 3 = outer limit of andalusite, 4 = outer limit of permeation (and sillimanite) and 5 = outer limit of injection. 5, 4 and 3 are undoubtedly related to the gneiss and the section suggests the possible similar relation of 2, but the status of 1 is unknown.

B. Generalized section across the Cooma Region showing eroded anticline invaded by Silurian gneiss and partly overlain by Upper Silurian strata on the east and by Tertiary basalt on the west.

There is evidence of the passage of albite solutions towards the west in the occurrence of a small mass of albitized gneiss on the western margin of the Cooma gneiss in Por. 161, Parish of Binjura. Moreover, *lit-par-lit* injection is better developed on the western margin of the intrusion; thus there is some evidence to show that pressure was directed from the east.

Heat no doubt played an important part in the metamorphism as well, and as the fluids were probably vehicles of heat, there would be a tendency for the rocks to be more greatly heated on the west.

VII. TECTONIC HISTORY OF THE COOMA REGION.

1. ORDOVICIAN.

From a study of the igneous and metamorphic histories of the area, an attempt was made to interpret the tectonic history of the Ordovician diastrophism (Joplin, 1942). This study throws some light upon the folding stage of the diastrophism, but until the Ordovician–Silurian boundary has been examined in great detail in a number of localities nothing can be said about the later stage of uplift.

Examination of the northern extension of the Cooma Complex has contributed little to the interpretation of the tectonic history, though there is some suggestion that compression was slightly less intense in the north. As outlined in the earlier paper the various phases of the folding stage appear to be as follows:

1. Compression and shearing stress.
2. Decline of shearing stress.

3. Static period.
4. Strong local compression.
5. Waning compression.
6. State of tension.
7. Renewal of slight compression mainly in south.
8. State of tension.

In Table I below, this succession of events is related to the magmatic and metamorphic history.

TABLE I.

Sequence of Events during the Folding Stage of the Ordovician Diastrophism.

TECTONIC.	MAGMATIC.	METAMORPHIC.
Compression and shearing stress.		Formation of chlorite- and possibly of biotite-schists.
Decline of shearing stress.	Injection of ultrabasic and basic magmas.	
Static period.	Slow upward movement of acid magma.	Weak contact-metamorphism with formation of andalusite — and possibly of biotite-schists.
Strong local compression, possibly greater in south.	Continued rise of acid magma with stromatolithic and *lit-par-lit* injection.	Formation of permeation (sillimanite)-zone, and injection-zone.
Waning compression.	Consolidation of main mass of granite : 1. Potassic. 2. Sodic.	
State of tension.	Injection of pegmatite dykes.	
Renewal of slight compression directed from east and confined mainly to southern region.	Albitization of pegmatites and albitization of Cooma gneiss on west.	Albite solutions squeezed out on west into permeation-zone. Internal evidence of post-consolidation stress in pegmatites.
State of tension.	Injection of quartz-plagioclase veins.	

2. SILURIAN.

The study of the Silurian has been limited to the igneous rocks, though a casual examination of the sedimentary rocks has revealed that they have suffered only a slight dynamic metamorphism. A slaty cleavage is well developed in the pelitic rocks, but fossils are still preserved in limestones and slates although sometimes they may be slightly sheared. The folding of these rocks is less intense than that of the Ordovician.

As the present work is a petrological study of the Ordovician rocks the effects of the Silurian diastrophism upon the Ordovician must be taken into account. The high-grade Ordovician schists have obviously been unaffected by the later movements, but the Bransby Beds, which were probably in the Ordovician chlorite-zone, show evidence of a Silurian dynamic metamorphism superimposed upon the contact alteration caused by the Silurian bathylith. Rhyolites and porphyries show intense crushing, and though this may be due to the Ordovician metamorphism, they exhibit slightly different features from the felsite sill occurring within the chlorite-zone on the west, and it seems likely that they received the greater dynamic metamorphism during the Silurian when temperatures were obviously lower and stress had a more marked, though a more local, effect. The Bransby Beds are characterized by the lenticular mode of fracture which has been laid down as a characteristic of pure dynamic metamorphism (Harker, 1932, p. 168). The limestones and pelites, however, with their "eye" structures about lime-silicate nodules and pyrites crystals, supply the best evidence of the age of the dynamic metamorphism and definitely place it after contact alteration by the Silurian gneiss.

The Silurian bathylith itself shows marked evidence of directed pressure. Thus dynamic differentiation has occurred and the pink and white gneisses have been developed on the eastern margin of the intrusion. The blue gneiss itself, especially in the prongs of the southern extremity of the bathylith, shows marked gneissic structure and a directional and concordant outcrop. The pressure appears to have come from the west and to have been of a recurring nature, but owing to the absence of granitization and *lit-par-lit* injection and to the presence of a limited contact-aureole, it seems evident that the magma was intruded and almost completely consolidated before being subjected to pressure. The fact that the blue gneiss is a primary gneiss, indicates that though solid, it was still hot at the time that it was stressed (Flett and Hill, 1912; Harker, 1932, p. 318). Further, at the time of this compression a liquid fraction was squeezed out, leaving the incompletely formed and somewhat rounded phenocrysts in the blue gneiss and subsequently consolidating as the white gneiss. Here again there is no evidence of the type of uplift that took place at the close of the Silurian, but some light is thrown upon the various phases of the folding stage of the diastrophic movement and these are listed below. Their correlation with the magmatic and metamorphic observations is shown in Table 2.

1. Compression and slight shearing stress.
2. Static period.
3. Compression directed from the west.
4. Static period.
5. Slight compression.
6. State of tension.

TABLE 2.

Sequence of Events during the Folding Stage of the Silurian Diastrophism.

TECTONIC.	MAGMATIC.	METAMORPHIC.
Compression and slight shearing stress.		Development of low-grade slates.
Static period.	Injection of magma and partial consolidation of blue gneiss.	Poorly-developed thermal aureole, " wet " contact-metamorphism and metasomatism. No granitization.
Compression directed from west.	Gneissic structures produced in blue gneiss and liquid fraction squeezed out on east, i.e., dynamic-differentiation.	Dynamic metamorphism superimposed upon contact-altered Bransby Beds. Very slight granitization near more acid rocks.
Static period.	Consolidation of white gneiss.	
Slight compression.		Gneissic banding and mortar structure produced in white gneiss.
State of tension.	Consolidation of massive pink gneiss in dykes.	

VIII. NATURE OF THE ORDOVICIAN AND SILURIAN BATHYLITHS.

Billings (1928) and Browne (1931) have distinguished and defined two types of bathylith, namely, synchronous and subsequent. Obviously both the Ordovician and Silurian bathyliths, invading the Cooma Region, belong to the synchronous type, but it is just as obvious that there are distinct differences between them. Thus the Ordovician bathylith is associated with highly schistose rocks and is surrounded by a zone of granitization. The occurrence of an andalusite-zone, however, points to a type of contact-metamorphism but it is a piezocontact metamorphism, which, according to Tilley (1925) is associated with a highly fluid magma. Furthermore, only extremely basic and extremely acid rocks occur within the bathylith and the main intrusion is highly contaminated.

The Silurian bathylith shows none of these features. The association of highly schistose Ordovician rocks with this is not genetic, and the Silurian rocks, with which it is not in contact, are only in a low grade of regional metamorphism. Granitization of the adjacent rocks is practically absent and the narrow contact-aureole is more closely comparable to that which surrounds a subsequent bathylith. The main body of the intrusion is an intermediate rock and shows no evidence of the assimilation of sediments.

Until the whole of the Murrumbidgee Bathylith has been examined it is impossible to discuss the cause of these obvious differences between two bathyliths that have been injected during a period of orogony, but observations in the neighbourhood of Cooma seem to suggest that the Ordovician magma was injected during a compressional phase whilst the Silurian bathylith was subjected to compression after it had partly consolidated. Nevertheless, depth of burial and the nature of the original magma are undoubtedly important factors in bringing about these differences, and when further data are accumulated a sub-division of the synchronous bathyliths may prove an interesting study.

IX. Summary.

Units higher in the Ordovician sequence than those met with at Cooma occur in the eastern part of the present area under discussion. These immediately underlie the Upper Silurian strata and have been termed the Bransby Beds. They consist largely of igneous and pyroclastic material and are described in some detail.

It is shown that the metamorphic zones mapped on the western side of the Cooma gneiss can be traced for several miles further north. It is also shown that, though similar zones occur on the east, these are much narrower than those of the west and are usually either contact-altered by, or engulfed by, an intrusion of Silurian gneiss. Possible reasons for this asymmetry of the zones are discussed.

Various differentiates, occurring at the southern extremity of the Silurian bathylith within this area, are described as well as their contact effects upon the Ordovician schists.

Finally, several phases of the folding stage of both Ordovician and Silurian diastrophisms are interpreted from a consideration of the magmatic and metamorphic histories of the whole region.

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